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A STUDY OF ELECTRON DENSITY PROFILES IN RELATION TO IONIZATION SOURCES AND GROUND-BASED RADIO WAVE ABSORPTION MEASUREMENTS, PART II

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ABSTRACT

The D-region ion production functions calculated in PART I of this work are used here in PART II to calculate the relationship between radio wave absorption and the flux level of X-rays in the 1-8 Å wavelength band. In order to bring this calculation into agreement with the empirically established relationship (Gnanalingam, 1974), we find it necessary to reduce by a factor of about 5 the Meira (1971) nitric oxide densities below 90 km.

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A STUDY OF ELECTRON DENSITY PROFILES IN RELATION TO IONIZATION SOURCES AND GROUND-BASED RADIO WAVE ABSORPTION MEASUREMENTS, PART II

1. INTRODUCTION

In PART I of this work (Gnanalingam and Kane, 1973) it was shown that current theory of the lower ionosphere in terms of the basic ionization production and loss processes cannot quantitatively explain the observed diurnal variation of radio wave absorption and virtual height. Here in PART II a further discrepancy in present day concepts is uncovered from an analysis of another set of radio measurements, namely measurements of absorption versus the level of solar X-ray activity. The measurements were made in Ceylon at noontime during the equinoctial months of 1968 through 1970 (Gnanalingam, 1974) and correspond to only moderate enhancements in solar X-ray activity, i.e., for the 1-8 Å flux level U in the range $4 \times 10^{-4} \leqslant U \leqslant 20 \times 10^{-4}$ ergs cm^{-2} sec^{-1}. What makes these measurements of particular interest is the fact that they furnish a constraint on one of the more critical constituents of the lower ionosphere, namely the nitric oxide density. Slight enhancements in the 1-8 Å solar X-ray flux can increase the electron density significantly in the altitude region near 85 km, and hence the measured absorption, but only if the ionization rate from the competing Lyman alpha-nitric oxide process is not too large.

In this report we attempt to interpret quantitatively the observed variation of absorption versus solar X-ray flux. Our starting point is, as it was in PART I, the noontime reference electron density profile N(ref) which was carefully constructed for the undisturbed solar condition $U = 4 \times 10^{-4}$ ergs cm^{-2} sec^{-1}. At slightly enhanced X-ray flux levels we can calculate a new electron density profile from the relation

$$N(\text{enhanced}) = N(\text{ref}) \times \sqrt{Q(\text{enhanced})/Q(\text{ref})}$$

where Q is the ion production function. This relationship is based on the plausible assumption that the effective electron loss coefficient remains unchanged during these slightly enhanced, non-flare solar flux conditions. For each enhanced electron density profile that we calculate we also calculate the corresponding radio wave absorption. From a comparison of the calculated absorption values with the observed absorption dependence on solar X-ray flux we conclude that our original undisturbed Q-function requires modification. We find that good agreement between calculation and measurement can most easily be obtained by reducing the Meira (1971) nitric oxide densities below 90 km by a factor of about five.

2. EXPERIMENTAL DATA

At Colombo, Ceylon, absorption measurements were carried out daily around noon, for many years, on the ordinary wave of several frequencies, including 2.0, 2.2, 2.6 and 3.2 MHz, by the vertical incidence pulse reflection (A1) method. The precautions taken to ensure accuracy in the measurements, and the estimated limits of error have been discussed previously (Gnanalingam and Ratnasiri, 1966). It is sufficient to state here that the absolute accuracy of the absorption data is better than ±2 dB. The absorption values obtained on the individual frequencies have been converted to a common frequency of 2.2 MHz and their mean value is taken as the daily noon absorption index. The measurements occupied a period of almost exactly one hour centered on 1200 hrs Local Standard Time. (At Colombo, Local Mean Time + 10.5 minutes = Local Standard Time = Universal Time + 5 hr 30 min.) Fortunately this period coincides with one of the hourly intervals for which published solar X-ray data are available.

In recent years a large body of X-ray data has become available through instruments mounted on satellites, principally the SOLRAD series of the U.S. Naval Research Laboratory. The detectors generally employed in these measurements are ionization chambers which, unfortunately, are also responsive to particle effects. Precautions are therefore necessary to detect the presence of particle interference and, as far as possible, filter out of the processed data the effects of this interference. This has been done in the case of the SOLRAD 9 measurements. The data series from this satellite begins in March 1968. The present analysis is restricted to this X-ray data.

In order to establish the quantitative relationship between absorption and 1-8 Å flux, the flux values were grouped into 0.5 millierg intervals, in ascending sequence up to 2.5 millierg, and the absorption values on the corresponding days were averaged for months having approximately the same solar zenith angle. The results obtained for the solar zenith angle $\chi = 10°$ are shown in Table I and plotted in Figure 1. The error bars represent the standard deviation of the individual absorption values about the mean for each flux interval. They reflect the spread in the data. The 95% confidence limits of the means are typically 1/2 to 1/5 of these values in extent, depending on the number of data points falling within each flux interval. The relationship between absorption and the 1-8 Å flux at $\chi = 10°$ is thus given by

$$L_{2.2} = 44.7 + (11.5 \pm 0.5)\sqrt{U} \qquad 0.4 < U < 2.0$$

TABLE I

Noon Absorption Corresponding to Different Levels of Solar 1-8Å flux During the Equinoctial Months (March, April, September, October) of 1968, 1969 and 1970: $\chi \simeq 10°$

Flux Interval in Milliergs cm^{-2} sec^{-1}	Number of Days	Mean of $\sqrt{U}$ Values $\sqrt{U}$	Standard Deviation of $\sqrt{U}$ Values	Mean of Normalized Absorption Values $L_{2.2}$ in dB	Standard Deviation of Normalized Absorption Values	Estimated* 95% Confidence Limits of True Mean $L_{2.2}$ in dB
$0 < U \leqslant 0.5$	72	0.621	0.066	52.09	2.41	52.1 ± 0.6
$0.5 < U \leqslant 1.0$	123	0.842	0.083	54.19	3.05	54.2 ± 0.5
$1.0 < U \leqslant 1.5$	54	1.098	0.068	57.69	2.92	57.7 ± 0.8
$1.5 < U \leqslant 2.0$	25	1.318	0.060	59.67	4.52	59.[illegible] ± 1.8
$2.0 < U \leqslant 2.5$	12	1.496	0.044	62.18	3.14	62.2 ± 1.9

*Not including a possible systematic error of less than ±2 dB resulting from uncertainties in the calibration constants, and equally applicable to all the normalized absorption values. The effect of such an error would be to offset the graphs shown in Figures 1, 4 and 5 by a constant amount vertically.

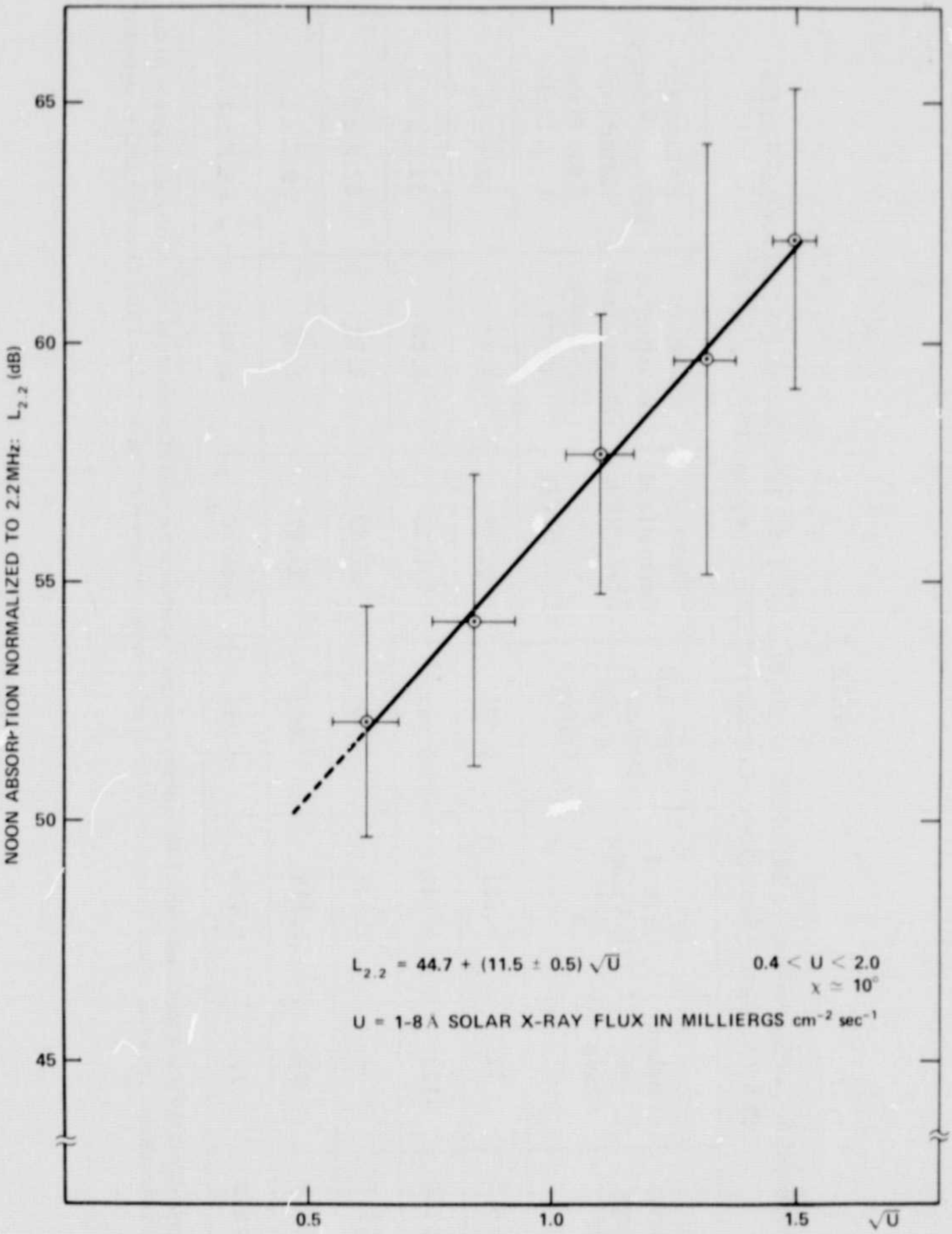

Figure 1. Relationship between absorption and 1-8 Å solar X-ray flux U, obtained at solar zenith angle $\chi = 10^\circ$. The error bars represent the standard deviation of the individual values about the mean in each flux interval. The 95% confidence limits of the means are typically 1/2 to 1/5 of these values depending on the number of data points falling in each flux interval.

where $L_{2.2}$ is the noon absorption normalized to 2.2 MHz and U is the 1-8 Å flux in milliergs cm^{-2} sec^{-1}.

In attempting to interpret this empirical result, it is important to remember that variations in the 1-8 Å flux are probably accompanied by variations in some of the other ionizing solar radiations. As discussed in PART I, the 30-40 Å flux plays a strong role in the ionization of the 88-94 km altitude range where most of the 2.2 MHz radio wave absorption occurs. Therefore it is conceivable that a significant portion of the absorption increase which has been attributed to the 1-8 Å flux (for moderate activity) is, in fact, caused by an accompanying increase in the 30-40 Å flux. We shall come back to this point later in Section 6 where we show that such an assumption is not necessary.

Another point that needs to be mentioned is the likelihood of there being some error in the absolute values of the 1-8 Å flux given in the published data. The reason is that the temperature and spectral distribution assumed for the solar X-ray emitting regions, so as to calculate the flux from the ionization chamber current, may not be in accord with the true characteristics of these regions (Kreplin, 1970; Horan, 1970).

3. REFERENCE ELECTRON DENSITY PROFILE

To interpret the above empirical relationship between absorption and X-ray flux, our starting point is the noontime reference electron density profile which we constructed in PART I for the conditions of an undisturbed sun at solar cycle maximum. This was done by combining the results of a noontime rocket measurement at Thumba, India with the results of multifrequency ground-based measurements made in Ceylon. The noontime ground-based measurements referred to in this instance were obtained on 72 days when the 1-8 Å flux was less than 0.5×10^{-3} ergs cm^{-2} sec^{-1} in the equinoctial months of 1968, 1969 and 1970 (Gnanalingam, 1974). For the lowest segment of our reference profile we adopted the electron density distribution derived by Kane (1969) from rocket-borne absorption measurements obtained at a solar zenith angle $\chi = 14°$. The uppermost portion of the reference profile was determined from well established empirical formulas which give as a function of solar cycle and zenith angle the height and density at the peak of the E-region. In the altitude region between 82 km and the peak of the E-region at 105 km our reference profile was adjusted by trial and error until good agreement was obtained between the results of the Colombo ground-based measurements and calculated values of absorption and virtual height.

In calculating these quantities from a given electron density profile (our collision frequency model is described in PART I) the generalized magneto-ionic

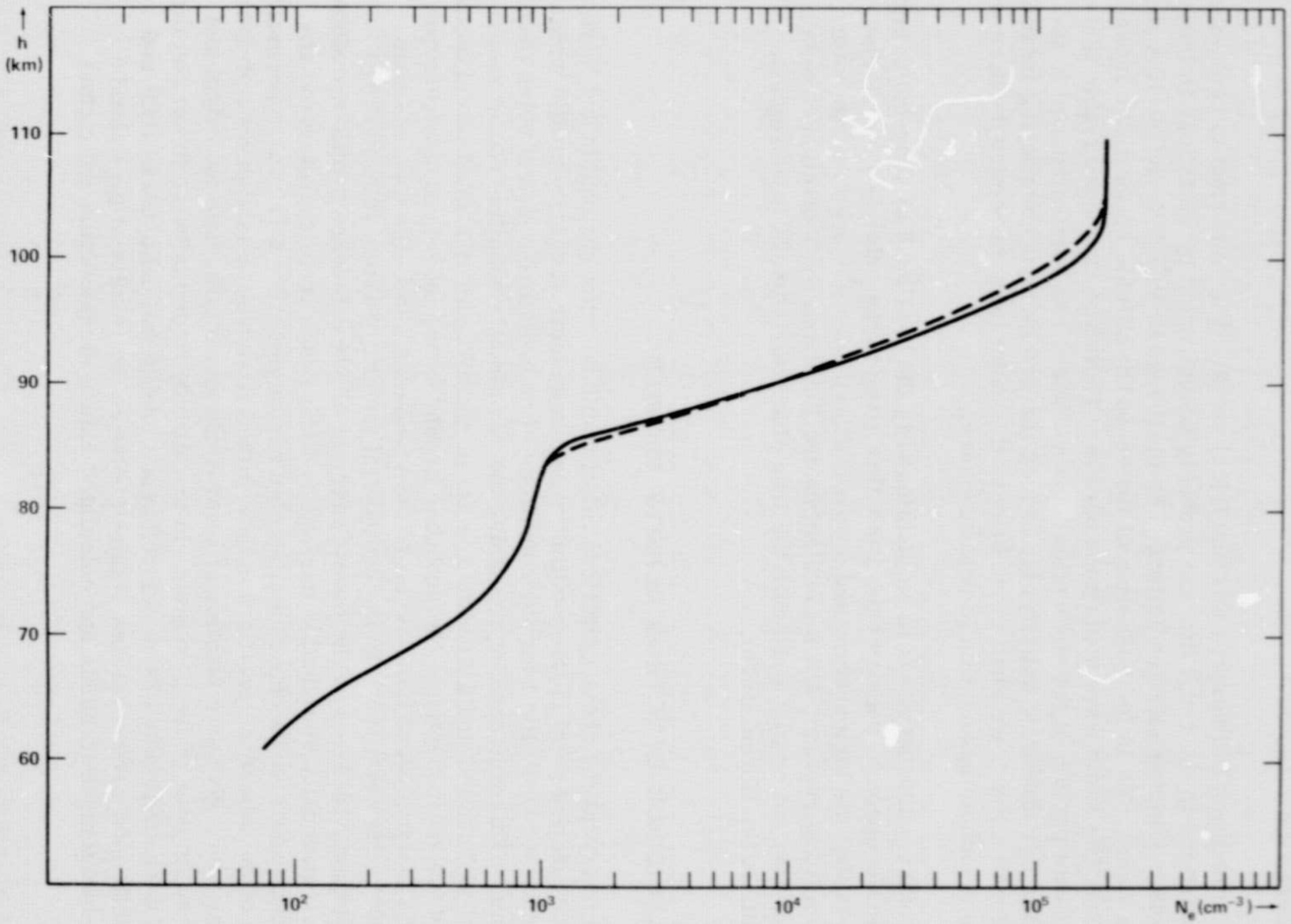

Figure 2. Reference electron density profiles for $\chi = 10^\circ$. Solid curve is deduced from mean values of multifrequency L,h′ measurements, while dashed curve is the profile allowed by the upper limit of error on the L,h′ measurements.

formulas of ray theory were used. To the absorption calculated by ray theory we added a phase integral correction (Thorpe, 1971) which, near the magnetic equator, is relatively small. At our exploring frequencies this combination of a ray theory calculation plus a phase integral correction gives a good approximation to a full wave solution. We estimate that the overall accuracy of the absorption calculated by this method is better than ±1.0 dB.

Our final reference profile to emerge from this procedure is shown as the continuous curve in Figure 2. Also shown as the dashed curve in Figure 2 is an alternative reference profile allowed by the confidence limits on the ground-based measurements.

4. ENHANCED ELECTRON DENSITY PROFILES

Starting from our reference electron density profile, we generate the profile corresponding to an enhancement in the 1-8 Å X-ray flux through our knowledge of the Q-function, i.e.,

$$N(\text{enhanced}) = N(\text{ref}) \times \sqrt{Q(\text{enhanced})/Q(\text{ref})}$$

This relationship ignores the possibility that an enhanced X-ray flux, by altering the ion composition, can modify the effective electron recombination coefficient α_{eff}. In Appendix A-1, where we examine this point in some detail, we conclude that for the purposes of the present work we can consider α_{eff} to be independent of the 1-8 Å flux level U at moderate values of $U \leqslant 2 \times 10^{-3}$ erg cm^{-2} sec^{-1}.

5. ION PRODUCTION FUNCTION

The ion production function Q was calculated in PART I of this work for the condition of an undisturbed sun at solar cycle maximum. The ingredients in that calculation were:

1. Groves (1971) model of the neutral atmosphere at 10° latitude at equinox extrapolated to 160 km by means of the Jacchia (1971) model thermosphere of 1100°K. Our model of the important constituent nitric oxide was taken from Meira (1971).

2. Best available estimates of the major ionizing radiations (Hinteregger et al., 1965, Hinteregger 1970, Manson, 1972).

3. Photon absorption cross sections and ionization yields based on a review by Swider (1969) together with tabulations given by Ohshio et al., (1966).

4. Minor contributions to the ionization rate from scattered Lyman-α and scattered Lyman-β radiation, from metastable $O_2(^1\Delta_g)$, and from galactic cosmic rays.

5. Satellite measurements of U, the energy flux in the 1-8 Å wavelength band, fitted to a bremsstrahlung type spectrum at a coronal temperature $T = 3.5 \times 10^6$ degrees K.

Here in PART II where our objective is to interpret the observed dependence of absorption on the 1-8 Å flux level, the Q-function calculation was repeated according to the following plan.

a. The 1-8 Å solar flux was increased through a range of values, assigning two different temperatures to the X-ray emitting regions; $T = 3.5 \times 10^6$ and $T = 7.0 \times 10^6$ degrees K. The first temperature value corresponds to an undisturbed sun at solar maximum (Neupert, 1969; Pounds, 1970). The second value is our estimate of the temperature of the X-ray active regions for a moderately disturbed sun with 1-8 Å flux in the range 2.0-2.5×10^{-3} ergs cm^{-2} sec^{-1}. This estimate was obtained by examining a large number of minute-by-minute listings of the fluxes in the 0.5-3 Å and 1-8 Å bands, from which ratio the temperature of the X-ray emitting regions may be deduced (Horan, 1970).

b. Step (a) was then repeated with allowance for an accompanying mild enhancement in the 30-40 Å flux F. Arbitrarily, we set $F = F_0(0.75 + 0.25U/U_0)$, i.e., we allowed F to increase by a factor of 2 for a factor of 5 increase in U.

c. Steps (a) and (b) were repeated for various nitric oxide distributions.

The results of these calculations, as reflected in the corresponding calculated electron density profiles, are discussed in the following section.

6. RESULTS

Figure 3a shows how, according to our knowledge of the Q-function, the electron density profile would change due to an enhancement in the 1-8 Å X-ray flux alone. In this example the coronal bremesstrahlung temperature is 7.0×10^6 degrees K, and the 1-8 Å flux is enhanced to 20×10^{-4} erg cm^{-2} sec^{-1}, whereas the temperature and flux values corresponding to the reference profile are 3.5×10^6 degrees K and 4×10^{-4} erg cm^{-2} sec^{-1}, respectively. We find that the resulting enhancement in electron density reaches a maximum of about 40% near 84 km. If we now further assume that this factor of 5 enhancement in

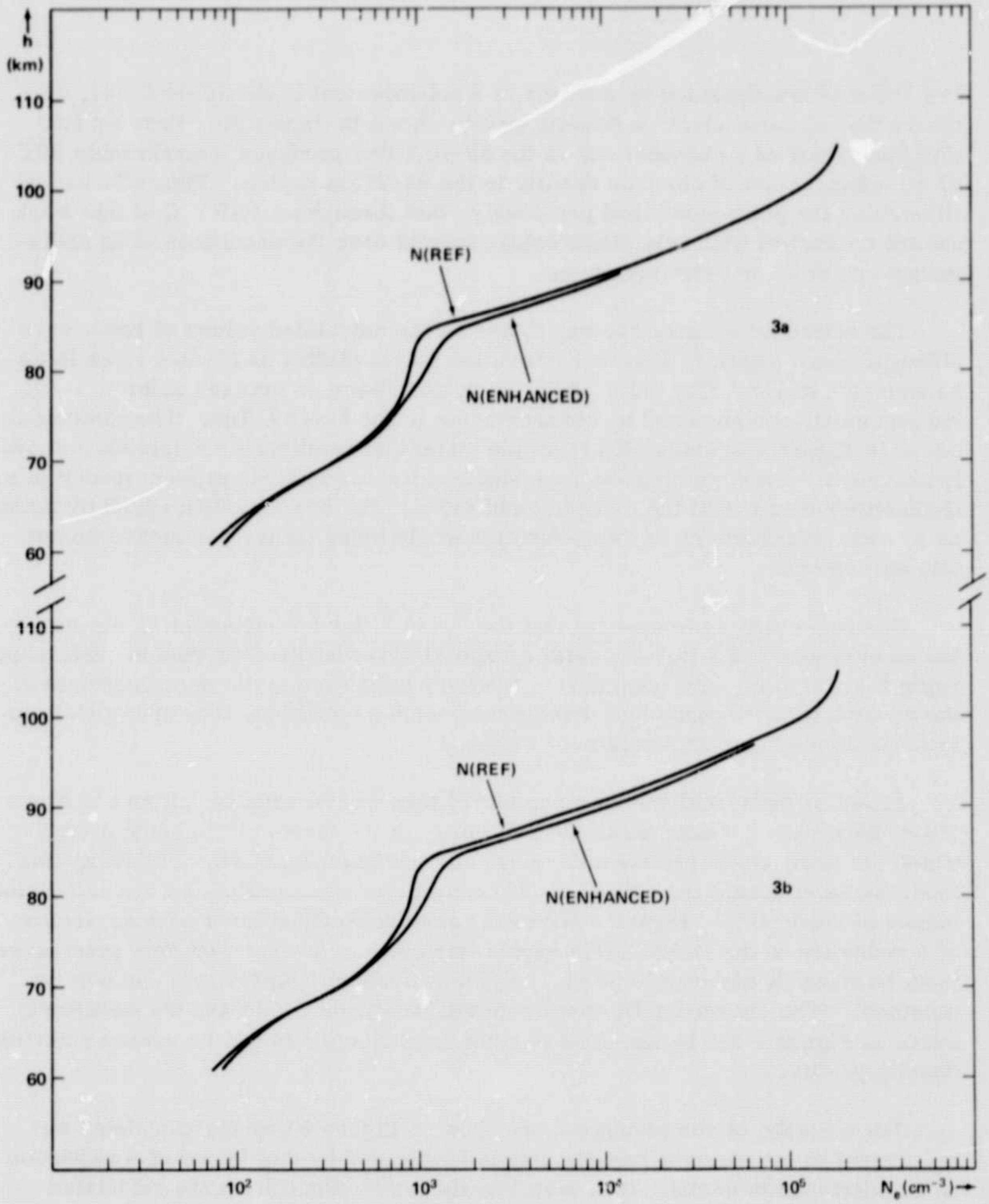

Figure 3a. Calculated electron density profile due to enhanced 1-8 Å flux $U = 2 \times 10^{-3}$ ergs $cm^{-2} sec^{-1}$ at a bremsstrahlung temperature $T = 7 \times 10^6$ degrees K. The reference profile N(ref) corresponds to the solar conditions $U = 3.5 \times 10^{-4}$ ergs $cm^{-2} sec^{-1}$ and $T = 3.5 \times 10^6$ degrees K. Figure 3b. Enchanced electron density profile corresponding to simultaneous enhancements in both the 1-8 Å and 30-40 Å wavelength band. The 1-8Å enhanced conditions are the same as those given for Figure 3a, while the 30-40 Å flux has been enhanced by a factor of 2 over its reference value.

1-8 Å flux is accompanied by a factor of 2 enhancement in the 30-40 Å flux, we obtain the enhanced electron density profile shown in Figure 3b. Here we find that this factor of 2 enhancement in the 30-40 Å flux produces a comparable 30% or so enhancement of electron density in the 92-97 km region. Figure 3a and b illustrates the point mentioned previously, that throughout PART II of this work we are concerned with only slight enhancements over the conditions of an undisturbed sun at solar cycle maximum.

The effects of enhanced X-ray fluxes on the calculated values of radio wave absorption are shown in Figure 4 where the points plotted as circles refer to enhancements of 1-8 Å flux only, while the points shown as crosses refer to 1-8 Å enhancements accompanied by enhancements in the 30-40 Å flux. The continuous curve in Figure 4 is calculated from the empirical relationship established above in Section 2. From an inspection of Figure 4 we see that our present theory (i.e., Q-function) does not fit the experimental facts. The question then naturally arises as to what modifications in the Q-function would bring theory and measurement into agreement.

One possibility is to assume that the 30-40 Å flux enhancement δF accompanies an enhanced 1-8 Å flux δU, with a ratio $\delta F/\delta U$ even greater than the arbitrary value 0.4 which we have used here. However until systematic measurements of the 30-40 Å flux are made that demonstrate such a condition, it is appropriate to look for an alternate explanation of Figure 4.

Based on their analyses of a number of ionospheric effects, Mitra and Rowe (1974) have raised doubts about the reliability of the Meira nitric oxide profile which for many years has been the generally accepted standard. Following this lead, we investigated the effects of different nitric oxide models on our calculated values of absorption. Figure 5 shows the results obtained for a constant factor of 5 reduction in the Meira nitric oxide distribution. We see that very good agreement between theory (circle points) and measurement (solid curve) can now be obtained. (The constant 1 dB offset between the circle points and the continuous curve in Figure 5 can be ascribed to some imperfection in our reference electron density profile.)

For the sake of completeness, we show in Figure 6 how the calculated enhancement in the electron density profile is affected by this factor of 5 reduction in the nitric oxide model. It is seen that this reduction affects the calculated electron density profile only below about 90 km. Equivalently we may say that our absoprtion data places a constraint on the nitric oxide distribution below 90 km, but not above that level.

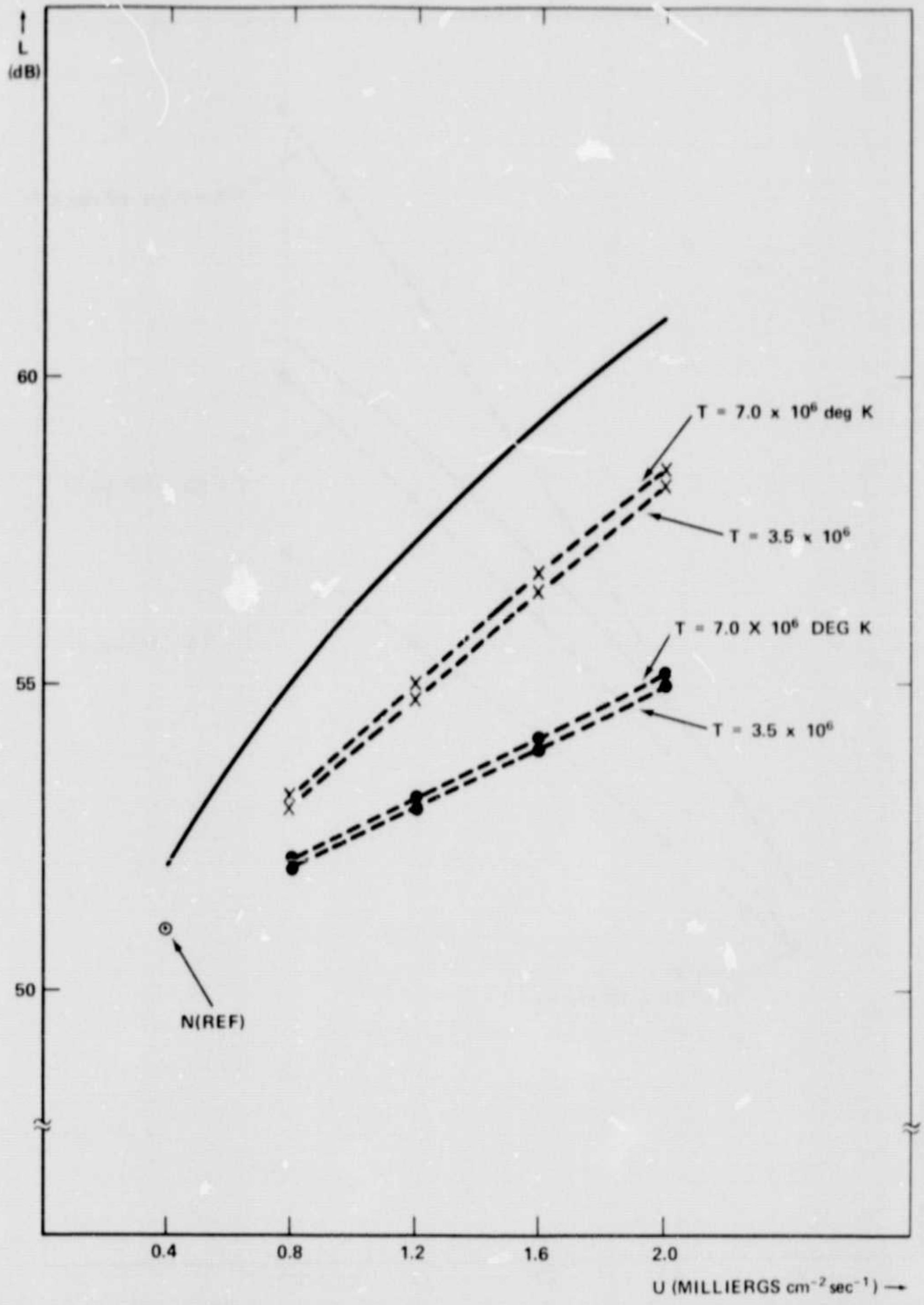

Figure 4. Failure of current theory. The predicted dependence of absorption on the 1-8 Å flux level is shown for two bremsstrahlung temperatures. The points shown as circles correspond to enhancements in the 1-8 Å flux alone, while the points shown as crosses correspond to enhancements in both 1-8 Å and 30-40 Å wavelength bands. The solid curve is the empirical relationship of Figure 1.

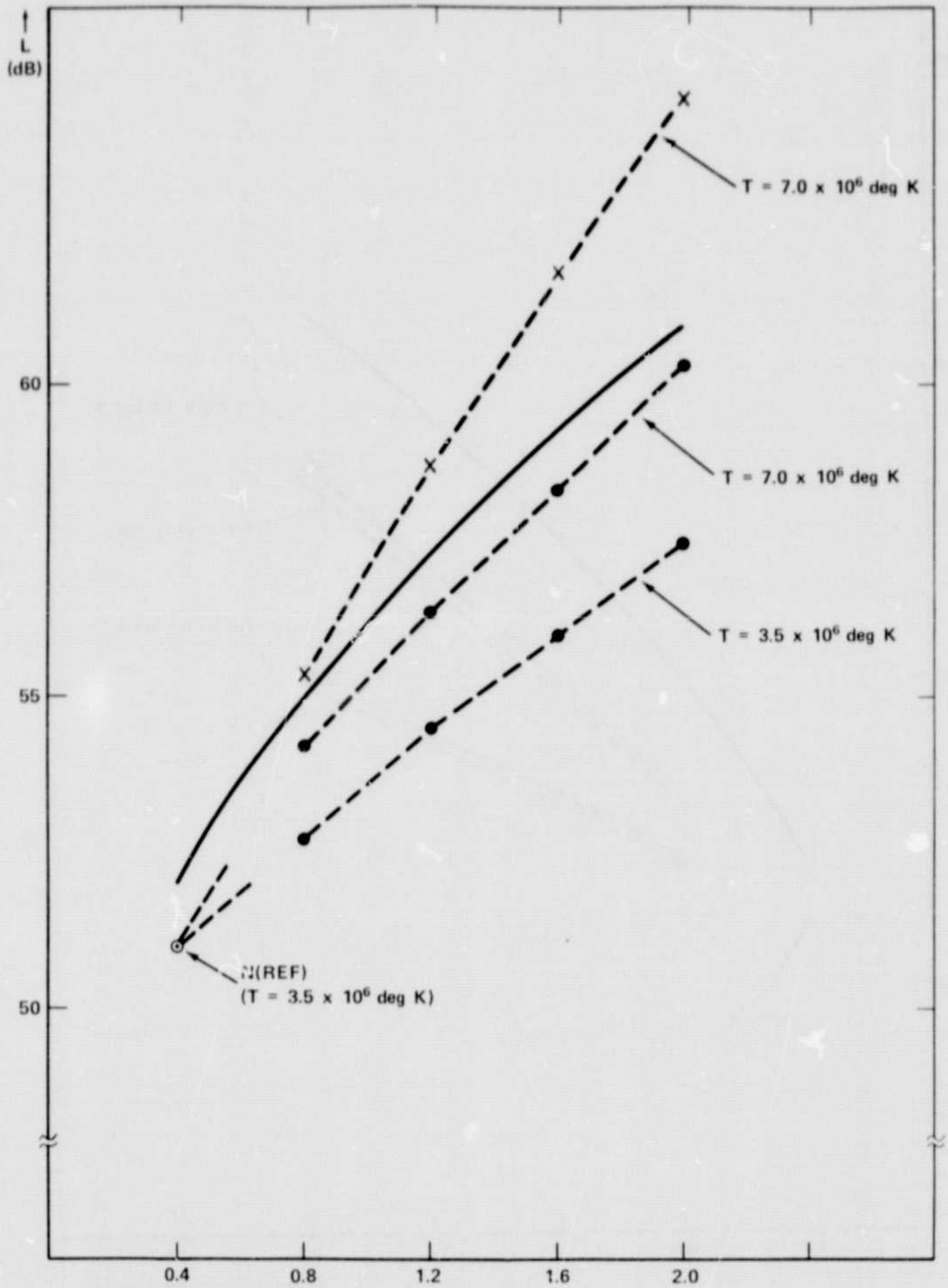

Figure 5. Comparison of experiment (solid curve) with theory based on reduced nitric oxide profile. The calculated values shown as circles correspond to enhancements in the 1-8 Å flux alone, while the points shown as crosses correspond to enhancements in both the 1-8 Å and the 30-40 Å wavelength bands.

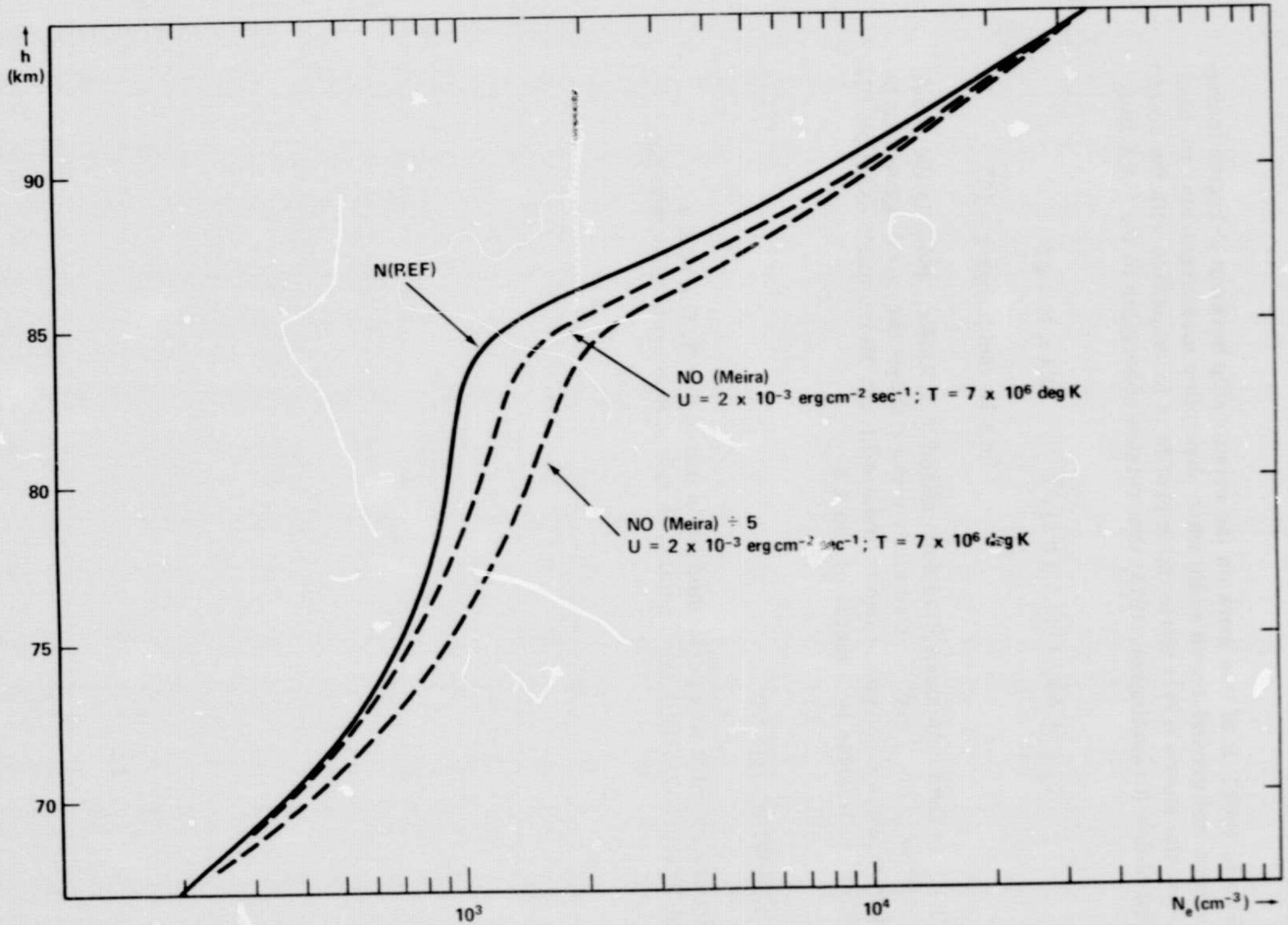

Figure 6. Effect of a Reduced Nitric Oxide Distribution on the Electron Density Profile's Sensitivity to a Given Flux Enhancement

7. CONCLUSION

Here in PART II of this work on the relationship between D-region ionization sources and ground-based radio wave absorption measurements, we have shown that the Meira (1971) nitric oxide profile is incompatible with the empirical expression (Gnanalingam, 1974) that relates absorption to the 1-8 Å flux, i.e.,

$$L_{2.2} = 44.7 + (11.5 \pm 0.5)\sqrt{U} \qquad 0.4 < U < 2.0$$

for solar zenith angle $\chi \simeq 10°$

where $L_{2.2}$ is the mean absorption normalized to 2.2 MHz, and U is the 1-8 Å flux in milliergs cm^{-2} sec^{-1}. Our study further shows that good agreement between theory and measurement can be obtained if the Meira nitric oxide profile below 90 km is reduced by a factor of about 5.

8. ACKNOWLEDGMENT

Part of this work was performed while one of us (S. G.) held a National Research Council Postdoctoral Resident Research Associateship.

APPENDIX A-1

Effective Electron Recombination Coefficient Versus Solar X-Ray Flux

In this work we have assumed that the effective electron recombination coefficient α_{eff} remains unchanged during moderate enhancements of the 1-8 Å X-ray flux U (i.e., $U \leqslant 2.0 \times 10^{-3}$ erg cm^{-2} sec^{-1}). This assumption is certainly not true when the magnitude of the flux enhancement approaches a solar flare condition. From an analysis of the ionospheric effects observed during some 25 flare events, Deshpande and Mitra (1971) have shown that α_{eff}, in the region of 80 km, undergoes a sharp decrease of an order of magnitude or more as the 1-8 Å flux level exceeds 10^{-2} erg cm^{-2} sec^{-1}. Since α_{eff} is determined by the ion composition, this decrease in α_{eff} implies a composition change-over from predominately cluster ions at low X-ray flux levels to predominately molecular ions at high flux levels.

In a theoretical study of solar flare effects on D-region ion chemistry, Mitra and Rowe (1972) have described a six ion chemical model (Table A-1) which they used to calculate the dependence of α_{eff} on X-ray flux. Their results for 80 km are shown in Figure A-1 for different assumptions concerning the concentrations of H_2O and O.

TABLE A-1

(Mitra & Rowe 1972)

Reaction	Rate
$O_2^+ + O_2 + O_2 \rightarrow O_4^+ + O_2$	6×10^{-30} cm^6 sec^{-1}
$O_4^+ + O \rightarrow O_2^+ \quad O_3$	1×10^{-10} cm^3 sec^{-1}
$O_4^+ + H_2O \rightarrow\rightarrow H^+\cdot(H_2O)_n$	1×10^{-9} cm^3 sec^{-1}
$O_2^+ + NO \rightarrow NO^+ + O_2$	8×10^{-10} cm^3 sec^{-1}
$O_2^+ + N_2 \rightarrow NO^+ + NO$	1×10^{-16} cm^3 sec^{-1}
$NO^+ + CO_2 \rightarrow\rightarrow H^+\cdot(H_2O)_n$	1×10^{-2} sec^{-1}

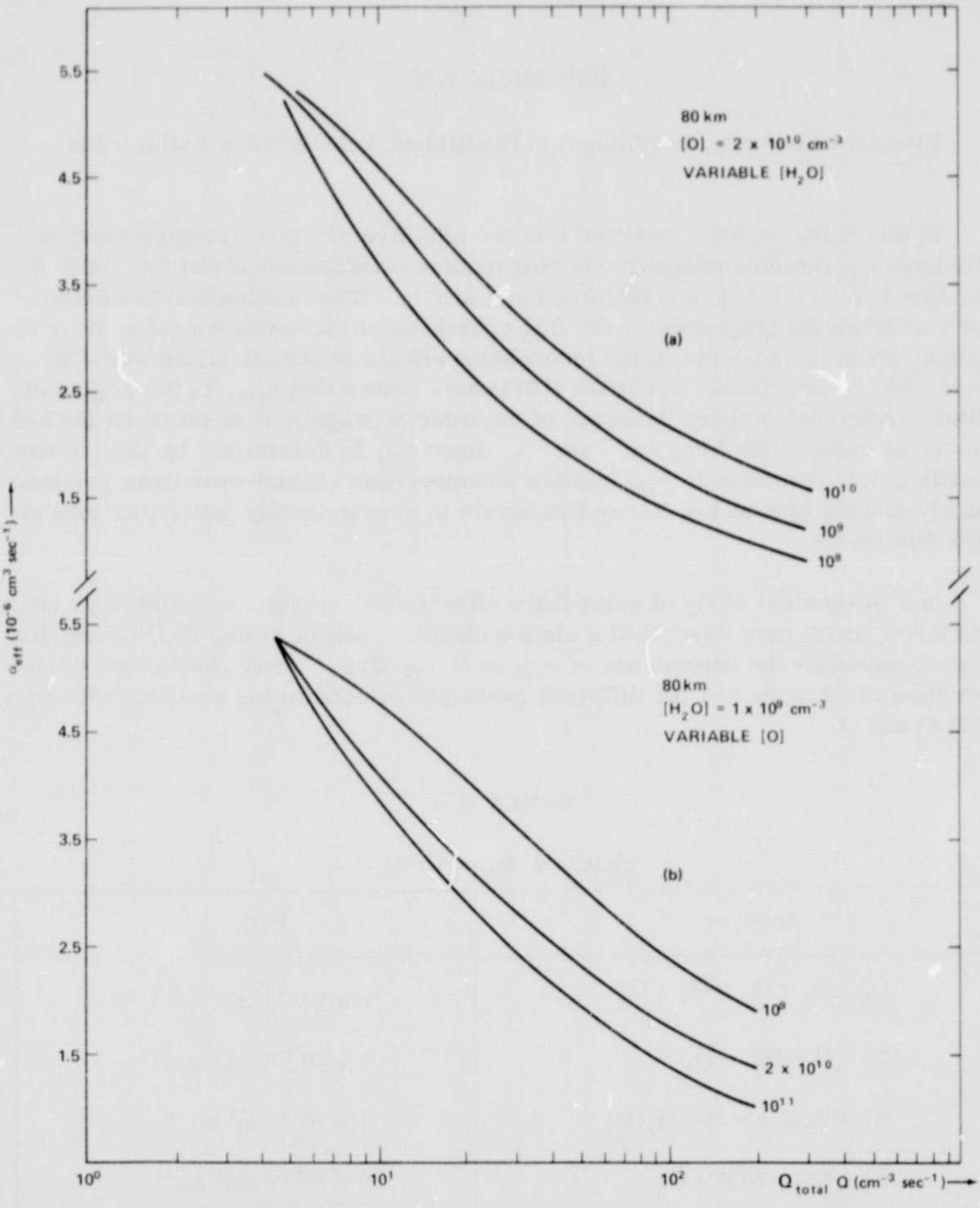

Figure A-1. (a) Calculated (Mitra and Rowe, 1972) Dependence of α_{eff} on the X-ray Flux Level (i.e., total Q-function) for Three Assumed Values of the Atomic Oxygen Concentration at 80 km; (b). Calculated (Mitra and Rowe, 1972) Dependence of α_{eff} on the X-ray Flux Level (i.e., total Q-function) for Three Assumed Values of the H_2O Concentration at 80 km.

For our present purpose we can approximate the middle curve of Figure A-1 by an expression

$$\alpha'/\alpha(\mathrm{ref}) = 1 - 0.4\,\ln(Q'/Q(\mathrm{ref})) \qquad \text{for } Q'/Q(\mathrm{ref})) \leqslant 2$$

and use this expression as a correction factor, to be applied below 85 km, on our calculation of the enhanced electron density profile N', i.e.,

$$N' = \underbrace{(N(\mathrm{ref}) \times \sqrt{Q'/Q(\mathrm{ref})})}_{\text{used in present text}} \times \underbrace{(\alpha'/\alpha(\mathrm{ref}))^{-1/2}}_{\text{correction factor}}$$

When this $\alpha(Q)$ correction factor is taken into account, we find that our calculated value of absorption, for the case $U = 2 \times 10^{-3}$ erg cm^{-2} sec^{-1}; $T = 7 \times 10^{6}$ degrees K, increases from 55.1 dB (see Fig. 4) to 56.0 dB. Clearly this additional 0.9 dB of absorption does not alter our main conclusion concerning the need for a reduced nitric oxide profile.

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